Binary and seismic modelling of the *Kepler* system KIC 10661783 with the δ Scuti component

Amadeusz Miszuda[1], Wojciech Szewczuk[1] and Jadwiga Daszyńska-Daszkiewicz[1]

1. Astronomical Institute, University of Wrocław, ul. Kopernika 11, 51-662 Wrocław, Poland

We present the results of the comprehensive study of the eclipsing binary system KIC 10661783 whose main component is a δ Scuti pulsating star. The Fourier analysis of the whole *Kepler* light curve, corrected for the binary effects, reveals 750 frequency peaks. Those with the highest amplitudes concentrate in the range of $20 - 30\,\mathrm{d}^{-1}$. The small-amplitude signals, found in the low-frequency range, can be a manifestation of gravity-mode pulsations. To reproduce the observed range of frequencies, we computed a grid of pulsational models. To obtain instability for high-order g modes, an increase of the mean opacity at the depth corresponding to the temperature of about 115 000 K was indispensable. For evolutionary computations the `MESA-binary` module was used to include interactions between the binary components.

1 Introduction

KIC 10661783 is a detached post-Algol binary system with a short orbital period $P \approx 1.2\,\mathrm{d}$ (Southworth et al., 2004). This is also a double-lined eclipsing binary with the stellar parameters of its components determined with an accuracy below 1.5% (Lehmann et al., 2013). It was studied for the first time by Pigulski et al. (2009), who reported that its light curve from the ASAS survey exhibits eclipses.

The system was observed by the *Kepler Space Telescope* for over four years. The light curve was analysed by Southworth et al. (2011). Using the short cadence (SC) Q2.3 and long cadence (LC) Q0–1 data, the authors found 68 frequency peaks. According to them, all observed frequencies originated from the primary component and they classified it as a δ Scuti variable. Later, Lehmann et al. (2013) determined the mass-ratio of the components from 85 spectra of the system. Its higher value than previously proposed by Southworth et al. (2011), suggested that the system is a post-mass transfer detached binary. Combining spectroscopic data and *Kepler* photometric observations the authors determined the fundamental stellar parameters of KIC 10661783 to be $M_A = 2.100(28)$ M$_\odot$, $R_A = 2.575(15)\,\mathrm{R}_\odot$ for the primary and $M_B = 0.1913(25)$ M$_\odot$, $R_B = 1.124(19)\,\mathrm{R}_\odot$ for the secondary. Here, we re-analyse the system using the *Kepler* data from all available quarters. Moreover, preliminary pulsational and binary-evolution modelling are presented.

2 Observations

KIC 10661783 was observed almost continuously for over four years by the *Kepler Space Telescope* in the two modes: short cadence and long cadence. Long cadence (LC, Q0-Q17) observations consist of over 58 000 data points covering 1 470 days

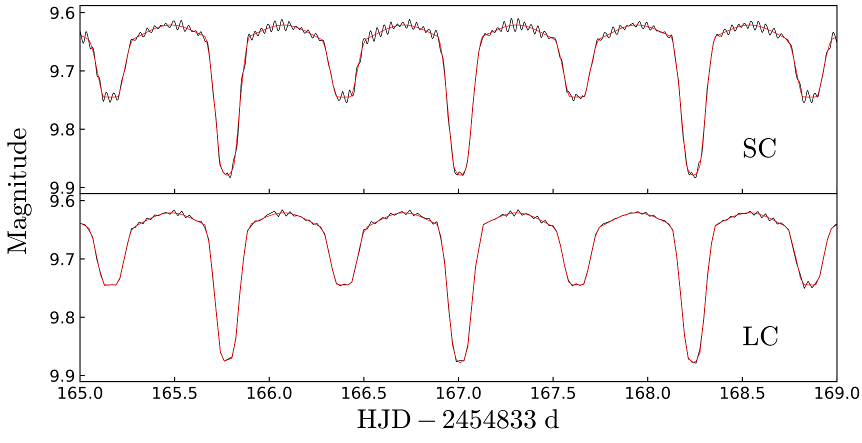

Fig. 1: A comparison of the *Kepler* light curve of KIC 10661783 from the short cadence (top panel) and long cadence (bottom panel) observations. To show both binary and pulsation variability only four days of observations are plotted. The calculated WD model is marked with the red line.

while short cadence (SC, Q2.3, Q6.1–Q8.3 and Q10.1–Q10.3) observations contain over 470 000 data points spread over 769 days period. A comparison of the light curves from the SC and LC modes is shown in Fig. 1 in the top and bottom panel, respectively.

3 Light curve modelling

Our modelling of the eclipse light curve was done in two steps. At first, we used the JKTEBOP code (Southworth et al., 2004) in order to obtain a good fit in a reasonably short time. Given over four years of almost continuous LC observations we are able to accurately determine orbital period, $P = 1.23136326(3)$ d. Next, with the new value of the orbital period, we modeled the system using Wilson-Devinney (WD, see Wilson & Devinney, 1971; Wilson, 1979) code in a detached mode. This allowed us to correct the light curve for the orbital variability. The fitted model of the light curve is plotted in Fig. 1 with the red line.

4 Binary evolution

Algol-type binaries are not well described by single-star evolution models, since no interactions between components are taken into account. To model the binary evolution of KIC 10661783 with mass transfer we used the binary module implemented in the MESA code (Paxton et al., 2011, 2013, 2015, 2018, 2019).

In order to fit in masses of the components, as determined by Lehmann et al. (2013), we built a grid of models with various initial masses of the primary component (acceptor) and of its companion (donor). We followed various scenarios of stellar evolution, assuming different mass distribution between stars, with a broad range of the initial orbital period. To reduce the mass accretion on the initially less massive component, we adopted a non-conservative mass transfer scheme, with only 50%

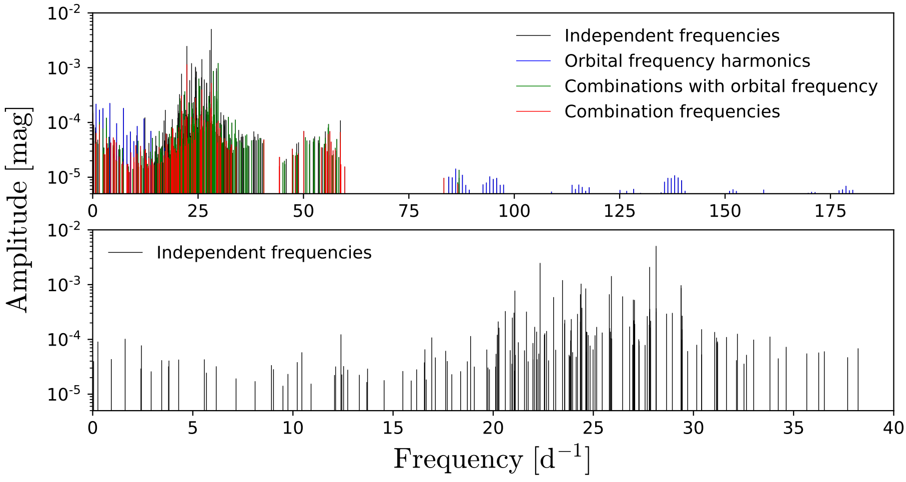

Fig. 2: Frequencies extracted from the SC data after subtraction of the orbital model. In the top panel, we plotted all frequencies found from the SC data. Blue peaks mark the orbital harmonics, green peaks are all combinations with the orbital frequency, red peaks mark other combinations and black peaks represent the independent frequencies and those with no equivalent in the LC data. The bottom panel shows only independent frequencies that have theirs equivalents in the LC data. Note that X-axis scales differ between the two panels.

of a total transferred mass being accreted. Our preliminary models reproduce the position of the acceptor on the HR diagram, however they fail to reproduce the parameters of the secondary star. Therefore, we are not able yet to properly establish the evolutionary status and age of KIC 10661783. More studies are required to unravel the present state and the past.

5 Frequency analysis and pulsational model of the main component

The Fourier analysis of both SC and LC data revealed a rich oscillation spectrum. Periodograms were calculated up to the Nyquist frequency for the SC data ($\sim$680 d^{-1}) and up to 200 d^{-1} for the LC data with the iterative pre-whitening procedure. A detailed analysis revealed 750 frequency peaks with the signal-to-noise ratio $S/N > 4.0$ in the SC data. The noise was calculated in a 1 d^{-1} window centred on a given frequency peak. Most of the observed frequencies from the SC data are located in the range $0 - 60$ d^{-1}. Above 85 d^{-1} we observe only high harmonics of the orbital frequency (up to $223 \times f_{\rm orb}$). No signal was found above 200 d^{-1}. In the case of the LC data, there is a problem with aliasing due to the low Nyquist frequency ($\sim$25 d^{-1}) but these data give better resolution and the extracted frequencies can be compared with those found from the analysis of the SC data. Using a simple procedure of finding combination frequencies ($m \times f_i + n \times f_j$) and the orbital harmonics ($N \times f_{\rm orb}$), we concluded that 167 amongst all, seem to be independent with the accuracy of the Rayleigh resolution for the SC data (0.0013 d^{-1}). These frequencies can be attributed to both pressure (p) modes and gravity (g) modes. All extracted frequency peaks are depicted in the top panel of Fig. 2 and the independent ones are

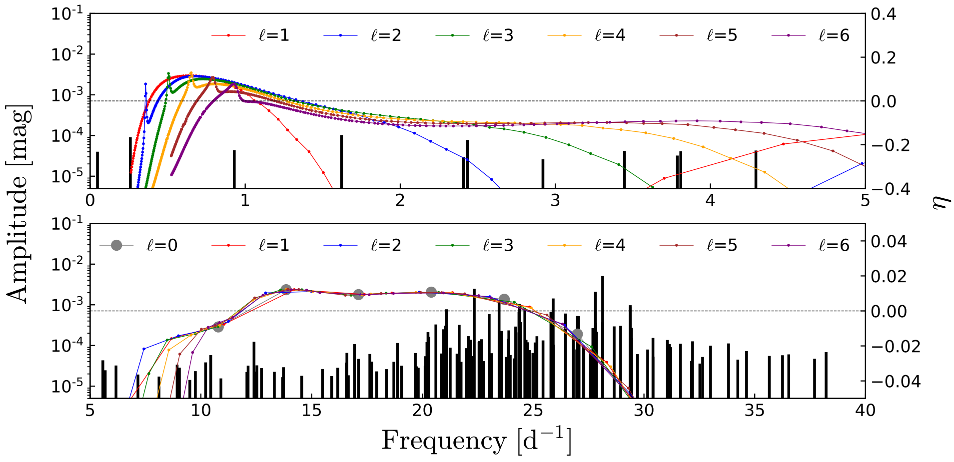

Fig. 3: The amplitude of the independent frequencies with the over-plotted values of the instability parameter η for the representative model of KIC 10661783 (see the text for the parameters). Modes with $\ell = 0 - 6$ are depicted. The model was computed with the OPAL opacities with an increase by 300% at $\log T = 5.06$. For clarity, only centroid modes ($m = 0$) are shown.

in the bottom panel of Fig. 2.

Low-frequency pulsations in δ Scuti stars face a problem because the current pulsational models computed with the standard opacity tables predict those modes to be stable. In order to fix that problem, the opacity increase at the depth corresponding to the temperature $T \approx 115\,000\,\mathrm{K}$ ($\log T = 5.06$) was proposed by Balona et al. (2015). This new opacity bump was identified by Cugier (2012) in the Kurucz model atmospheres.

We computed the pulsational model for the main component of KIC 10661783 with the modified OPAL opacities (Iglesias & Rogers, 1996) adopting the following parameters: $M = 1.86\,\mathrm{M}_\odot$, $R = 2.408\,\mathrm{R}_\odot$, $\log T_{\mathrm{eff}} = 3.8958\,\mathrm{K}$, $\log L/\mathrm{L}_\odot = 1.300$. The modification of the mean opacity profile consisted in artificially increasing the opacity at $\log T = 5.06$ by 300%. Modes with the harmonic degree $\ell = 0 - 6$ were considered.

In Fig. 3, we show the oscillation spectrum of the δ Scuti component with the over-plotted run of the normalized instability parameter η as a function of the frequency. The positive value of η means that a given mode is excited. If we take into account rotational splitting we obtain unstable modes covering the whole g-mode region.

6 Conclusions

The aim of the paper was to present the preliminary results of the comprehensive study of the binary KIC 10661783 with the δ Scuti variable as the primary. Our analysis consisted of the modelling of the eclipse light curve, pulsational modelling of the main component and computations of binary evolution. First, we analysed all available *Kepler* photometric data and redetermined the orbital period. Then, the binary model was subtracted from the SC light curve and the Fourier analysis revealed 750 frequency peaks in the range of $0 - 200\,\mathrm{d}^{-1}$ from which 167 are independent. The highest-amplitude peaks concentrate in the range of $20-30\,\mathrm{d}^{-1}$. This range is typical for a not-evolved δ Scuti star as far as single evolution is concerned. However, here we are dealing with the evolution in the binary system which has caused the rejuvenation of the main component, which was originally a less massive star.

In addition to those frequencies typical for δ Sct pulsators we found low-frequency signals that can be interpreted as high-order g-modes. Such modes are not excited in the standard opacity models for these stars. To account for these frequencies, we computed the pulsational model with opacities modified at $\log T = 5.06$. This helped to increase the value of the instability parameter η for low frequency modes, but the model is still not satisfactory and further studies are needed.

Finally, we constructed binary-evolutionary models which account for the position on the HR diagram of the main component. More detailed modelling, reproducing masses and radii of both components as well as all orbital parameters, will be presented in a separate paper.

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